Preprint
UCRL-JC-135697

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This article was submitted to
8th International Workshop on Low Temperature Detectors, Dalfsen, The Netherlands, August 15-20, 1999

August 30, 1999

U.S. Department of Energy

Lawrence Livermore National Laboratory

This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

NOVEL REFRIGERATOR DEVELOPMENT

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ABSTRACT
In part I, we describe how the creation of quasiparticles by current flow through a normal-insulator-superconductor (NIS) junction degrades the cooling performance of the junction. Degradation occurs due to the absorption of recombination phonons in the normal electrode and due to a reduction in the cooling power. In part II, we describe how vibrations from a pulse tube mechanical cooler affect X-ray measurements performed with a superconducting tunnel junction.

I-NIS COOLING

Since the first demonstration of electron cooling by NIS tunnel junctions [1], there has been interest in the development of on-chip refrigerators having base temperatures near 100 mK when operated from bath temperatures of several hundred mK. [2,3] Here, we show how heating of the electron system in the superconducting electrode of a NIS junction can degrade refrigerator performance.

Current flow through a NIS tunnel junction heats the electron system in the superconducting electrode through the creation of quasiparticles. This heating degrades the cooling performance of the junction in two ways. First, quasiparticle recombination produces phonons which can travel through the tunnel barrier and heat the normal electrode. Second, the power removed from the normal electrode decreases as the quasiparticle density in the superconductor increases. Electrons which tunnel from below the Fermi level of the normal metal and fill hole-like excitations in the superconductor are especially detrimental to the cooling power. The two degradation mechanisms are described quantitatively below.

If the quasiparticle density in the superconducting electrode is $n_x + n_{th}$ where n_{th} is the thermal density, then the recombination rate is $\Gamma_R (n_x + n_{th})^2 V_S$ quasiparticles per second where Γ_R is the recombination rate per unit density and V_S is the volume. The power load on the normal electrode due to phonons is then given by $\Gamma_R (n_x^2 + 2n_x n_{th}) V_S \, \Delta \, p_{p-e}$ where Δ is the energy gap and p_{p-e} is the probability a phonon excites an electron in the normal electrode.

The power deposited in the superconducting electrode of a NIS junction is given by

$$P_S = \frac{1}{e^2 R_N} \int_{\Delta}^{\infty} EN(E)[f_N(E+eV_b) + f_N(E-eV_b) - 2f_S(E)]dE \qquad (1)$$

where R_N is the resistance, $N(E)$ is the energy-dependence of the superconducting density of states,

V_b is the bias voltage, and f_N (f_S) is the Fermi function in the normal (superconducting) electrode. We assume that the electrons in the normal metal (superconductor) have an effective temperature T_N (T_S). The cooling power in the normal electrode, P_N, is $P_S - IV_b$. In Fig. 1, we plot the normalized cooling power as a function of T_S/T_N for T_N equal to 0.1, 0.2, and 0.3 K and Δ =180 μeV. The cooling power decreases when T_S exceeds T_N. The loss in cooling power due to heating in the superconductor is given by $P_N(T_N, T_S) - P_N(T_N, T_S = T_b)$ where T_b is the bath temperature.

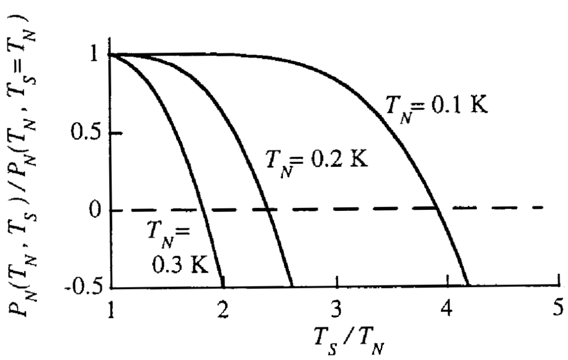

fig. 1 Cooling power P_N with normal electrode temperature T_N and superconducting electrode temperature T_S plotted versus T_S/T_N for T_N =0.1, 0.2, and 0.3 K. The result is normalized by P_N evaluated with $T_S = T_N$. The bias is 0.95 Δ/e.

Previous experimental work described deviations from the expected thermal behavior in terms of a power load on the normal electrode $\beta P_S(T_N, T_S = T_b)$. [3] This description implies that a fraction β of the power deposited in the superconductor, P_S, returns to the normal electrode. The fraction β was measured to be 0.125-0.15 for T_b of 0.2-0.3 K and V_b of 0-1.1Δ/e. The same β was found for 2 junctions with lengths of 20 and 15 μm, areas of 400 and 150 μm^2, and specific resistances of 3300 Ωμm^2 and 7200 Ωμm^2, respectively. We next describe how to calculate β.

To estimate the power load due to quasiparticle recombination and the loss in cooling power due to values of $T_S > T_b$, we calculate the quasiparticle density in the superconductor. This is equivalent to calculating T_S. The spatially varying excess quasiparticle density, $n_x(x)$, is given by $D\nabla^2 n_x - \Gamma_R(n_x^2 + 2n_x n_{th}) + \Gamma_{QP}\, g(x) = 0$ where D is the diffusion constant. The end of the junction is a mirror and the point where the superconductor overlaps a normal contact pad is a sink. The function $g(x)$ describes the injection geometry. The rate of quasiparticle injection, Γ_{QP}, is given by Eq. (1) without the factor of E inside the integral. Since Γ_{QP} is a function of T_S and thus n_x, we solve for n_x iteratively until a self-consistent solution is found.

Calculated values of n_x due to currents of 1.67 μA (solid line) and 6.84 μA (dashed line) are plotted in Fig. 2. These currents correspond to V_b = 0.75Δ/e and 1.0Δ/e, and T_N = 0.3022 and 0.3086 K, respectively. The bath temperature was 0.304 K. The injection region extends from x=0 to x=20 μm and the quasiparticle sink occurs at x=47.5 μm. Including phonon trapping, we calculate Γ_R=30 μm^3/s. The diffusion constant D is calculated from resistivity measurements and the quasiparticle dispersion relation. A value for D of 9×10^9 μm^2/s is typical, but there is a weak dependence on V_b, T_N, and T_S. To simplify, we set T_S equal to T_b when calculating D. The excess densities of 10,500 μm^{-3} and 37,300 μm^{-3} in the junction correspond to T_S= 0.371 and 0.447 K, respectively.

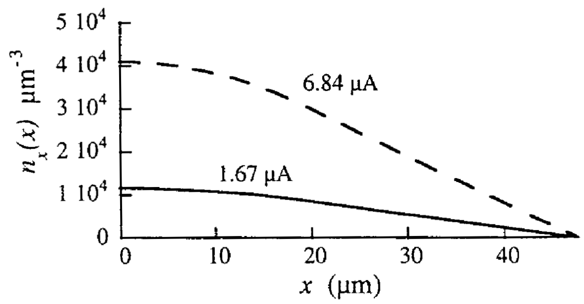

fig. 2 Excess quasiparticle density $n_x(x)$.

Given n_x and T_S in the superconducting electrode of the junction, we can calculate β. Based on phonon-electron and phonon escape rates, we estimate p_{p-e} is 0.4. We conclude that for I=1.67 μA, recombination produces a power load of 4 pW on the normal electrode. The decrease in cooling power due to elevation of T_S above T_b is also significant. We calculate from Eq. (1) that the cooling power is reduced by 11 pW. Summing these powers and dividing by Eq. (1) evaluated with T_S=T_b, we arrive at β=.05. For I=6.84 μA, the recombination load is 37 pW, the decrease in cooling power is 42 pW, and β is .06. These predictions for β incorporate no free parameters and agree with measurement to factors of 2-3. The predictions are largely independent of bias, in good agreement with measurement. Calculations carried out at T_b=0.226 K yield similar values of β. Hence, predictions for β are independent of T_b over the range 0.2-0.3 K, also in good agreement with measurement. The predicted values of β can be increased to 0.125-0.15 by decreasing the mean free path by a factor near 3.

The predicted values of β for the 15 μm long junction in [3] are smaller: .02-.03. It is surprising that β measured in the 15 μm and 20 μm junctions is the same because of the higher specific resistance and shorter distance quasiparticles need diffuse before leaving the smaller junction. It is possible that the mean free path in the Al of the smaller junction is shorter than in the larger because shadow mask deposition produces more disorder in small features.

In conclusion, we have successfully developed techniques to calculate the degradation in NIS refrigerator performance caused by heating of the superconducting electrode. This heating can be reduced by using a thick, clean film for the electrode, by placing a quasiparticle trap near the junction, and by using a short junction.

II-CRYOGEN-FREE REFRIGERATION

Detectors operating below 1 K will be powerful tools for materials microanalysis because of their ability to accurately measure X-ray energies. [4] Cryogenic detectors may also prove useful for mass spectrometry of heavy biological molecules. [5] Both these activities are commonly pursued outside low temperature physics laboratories. As a result, there is a clear need for simple, reliable, *closed-cycle* refrigeration equipment. A candidate system might consist of a two stage adiabatic demagnetization refrigerator (ADR) capable of cooling from 4 K to 100 mK coupled to a mechanical cooler capable of cooling from 300 K to 4 K. While mechanical coolers able to reach 4 K have existed for a number of years, there has been persistent concern that the vibration produced by these coolers is incompatible with the operation of sensitive electronics. However, the recent development of pulse tube mechanical coolers capable of reaching 4 K has renewed interest in closed-cycle systems because of the low vibration of the pulse tube. [6] We have coupled a pulse tube to an ADR cooled by liquid cryogens in order to measure how the vibration of the pulse tube affects the resolution of superconducting tunnel junction (STJ) detectors.

We mounted a Cryomech PT4-05 pulse tube in a dewar adjacent to a second dewar containing a single stage ADR. A rigid cold finger joined the second stage of the pulse tube to the 4.2 K stage of the ADR. We measured X-rays with Nb-Al-AlOx-Al-Nb STJs both with and without the pulse tube operating at its base temperature of 2.8 K. As shown in Fig. 3, the energy resolution of the STJs was degraded from 26 eV to 30 eV by the vibration of the pulse tube when measuring 1.04 keV Na K shell X-rays. This degradation corresponds to a 15 eV noise source added in quadrature. Spectral analysis of the detector baseline showed that operation of the pulse tube added several noise peaks between 3 and 50 kHz. Since no effort was made to mechanically or electrically isolate the ADR from the pulse tube, we believe this first effort is encouraging. It is hoped these results will spur development of closed-cycle refrigeration systems for cryogenic detectors.

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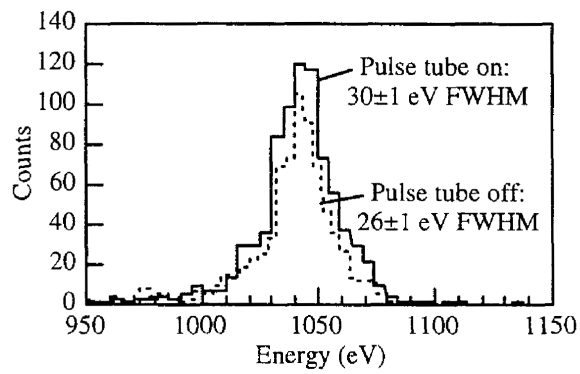

fig. 3 Effect of pulse tube vibrations on energy resolution of STJ detector for 1.04 keV X-rays.

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